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Stockpile Stewardship and The Surrogate Reaction Technique

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Nuclear Reactions on Unstable Nuclei and the Surrogate Method
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DOE's Long Range Plan

RIA tied for 3rd highest priority for new large science facilities.

- **DOE's released its 20 year plan for new science facilities released on November 10, 2003, by Secretary Abraham.**
- **Excerpt from Report:**

  "It will allow physicists to explore the structure and forces that make up the nucleus of atoms; learn how the chemical elements that make up the world around us were created; test current theories about the fundamental structure of matter; improve our ability to model the explosions of nuclear weapons, and play a role in developing new nuclear medicines and techniques."

Stockpile Stewardship

Stockpile Stewardship is DOE program to improve modeling capability of nuclear explosions.

Key challenge in past nuclear weapon tests is measuring neutron flux during test.

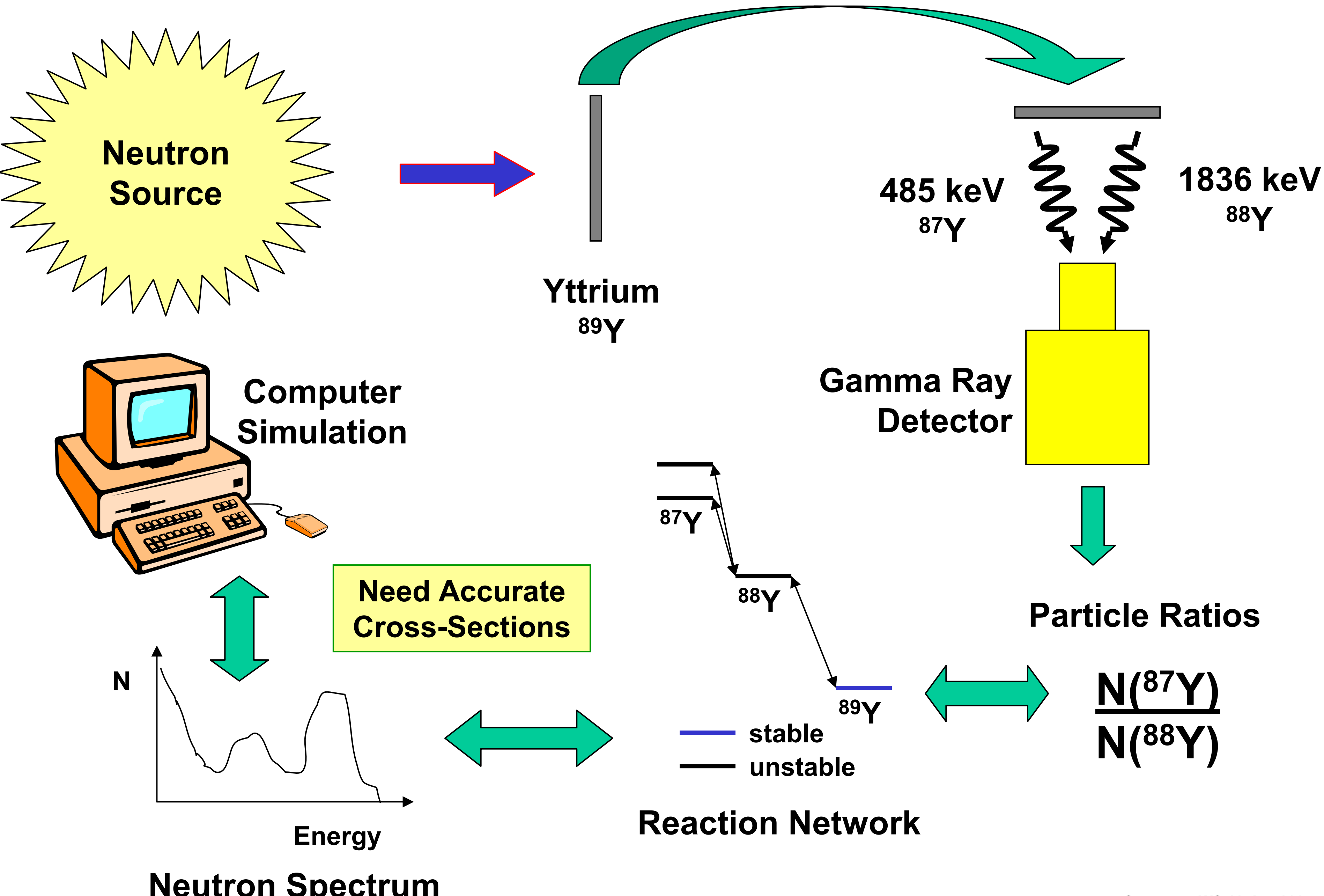
Answer: Use certain isotope as neutron flux monitors.

1. **Load isotope into device.**
2. **Extract core sample after test and perform radiochemical processing.**
3. **Interpret measured isotope production to infer information about neutron flux (neutron cross-sections needed).**

Key challenge at present is to reduce uncertainty of interpretation.

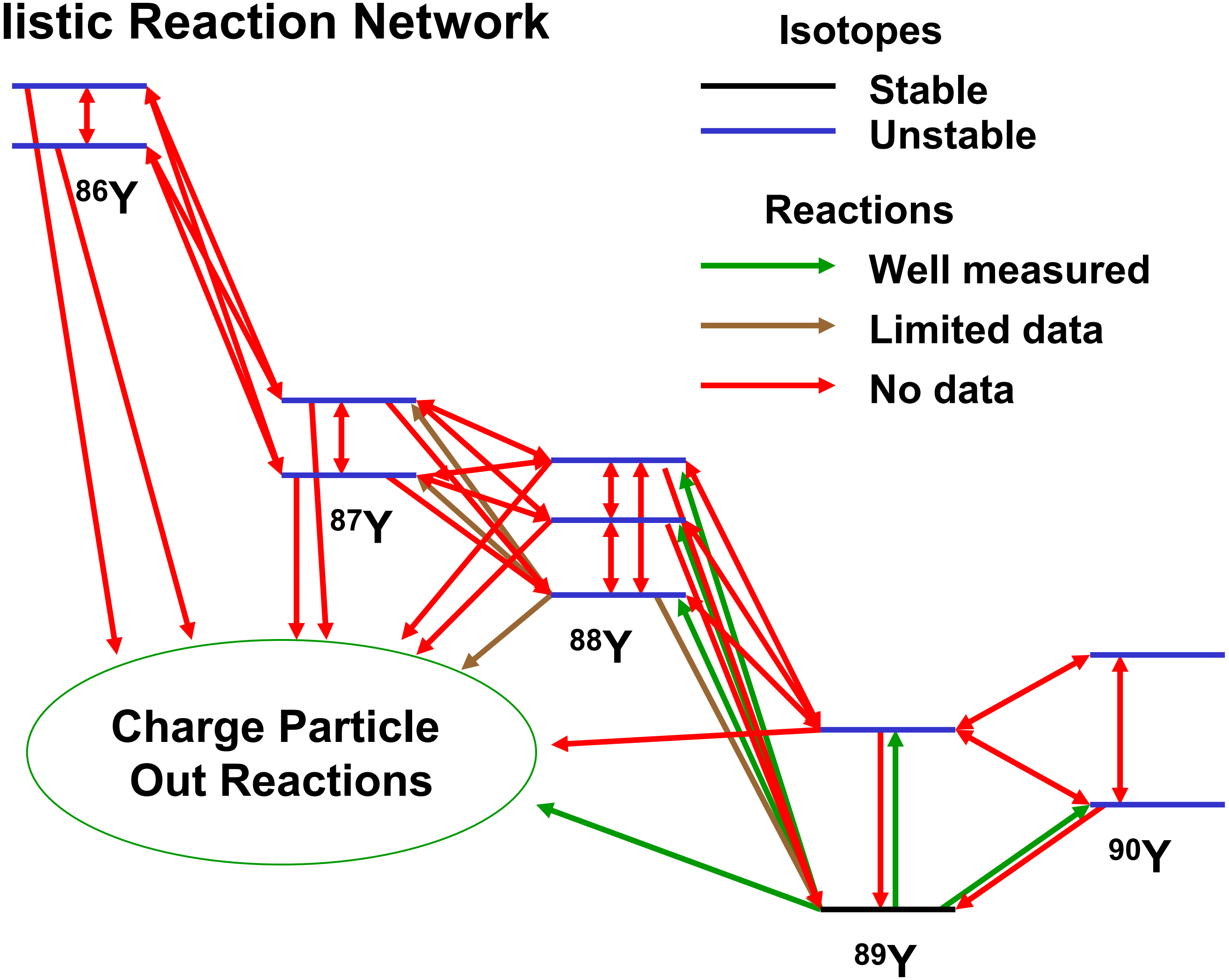
Answer: Improve quality of neutron cross-section data.

Using Isotope Production To Determine Neutron Flux



Reaction Networks Are Complex

More Realistic Reaction Network



1. Most reactions involve unstable isotopes.
2. Most reactions have no data to verify calculation.

Neutron Reactions Important to Stewardship

Reaction	Energy Range (Mev)	Importance	Accuracy
(n,γ)	0.01- 0.2	High	10%
(n,n’)	1-10	Low	10%
(n,2n)	10-16	High	3-5%
(n,pX), (n,α)	0.1-16	Medium	10%
(n,f)	0.1-16	High	1-2%

Some Relevant Reaction Networks

Loaded Element	# of isotopes and isomers	# with half-life > 10y	# with half-life < 1d
Ti	14	6	3
Cr	11	3	4
Fe	5	2	1
Br	6	4	1
Kr	3	2	0
Y	11	1	6
Zr	10	3	5
Nb	5	3	1
Mo	3	1	2
Eu	20	7	5
Tm	8	1	2
Lu	24	2	14
Ta	6	2	1
Ir	21	3	12
Au	7	1	1
Bi	7	3	1

A number of different monitors have been used.

Almost all have isomers or very short lived nuclei.

Some reaction networks include isotopes of neighboring elements.

Not included in this list:

- **Actinides – U, Np, Pu**
- **Prompt fission fragments**

Challenges of Neutron Cross-Section Measurements

Neutron cross-section measurements on unstable nuclei are difficult because of low event rates and high background rates.

Neutron flux typically much smaller than charge particle beam fluxes.

- **Flux of RNTS-2 at 10 cm from production target: $5x10^{10}$ n/cm^2/s.**
- **Flux of 1 pnA charge particle beam with 2 mm beam spot: $2x10^{11}$ p/cm^2/s.**
- **Difficult to manipulate neutrons after production.**

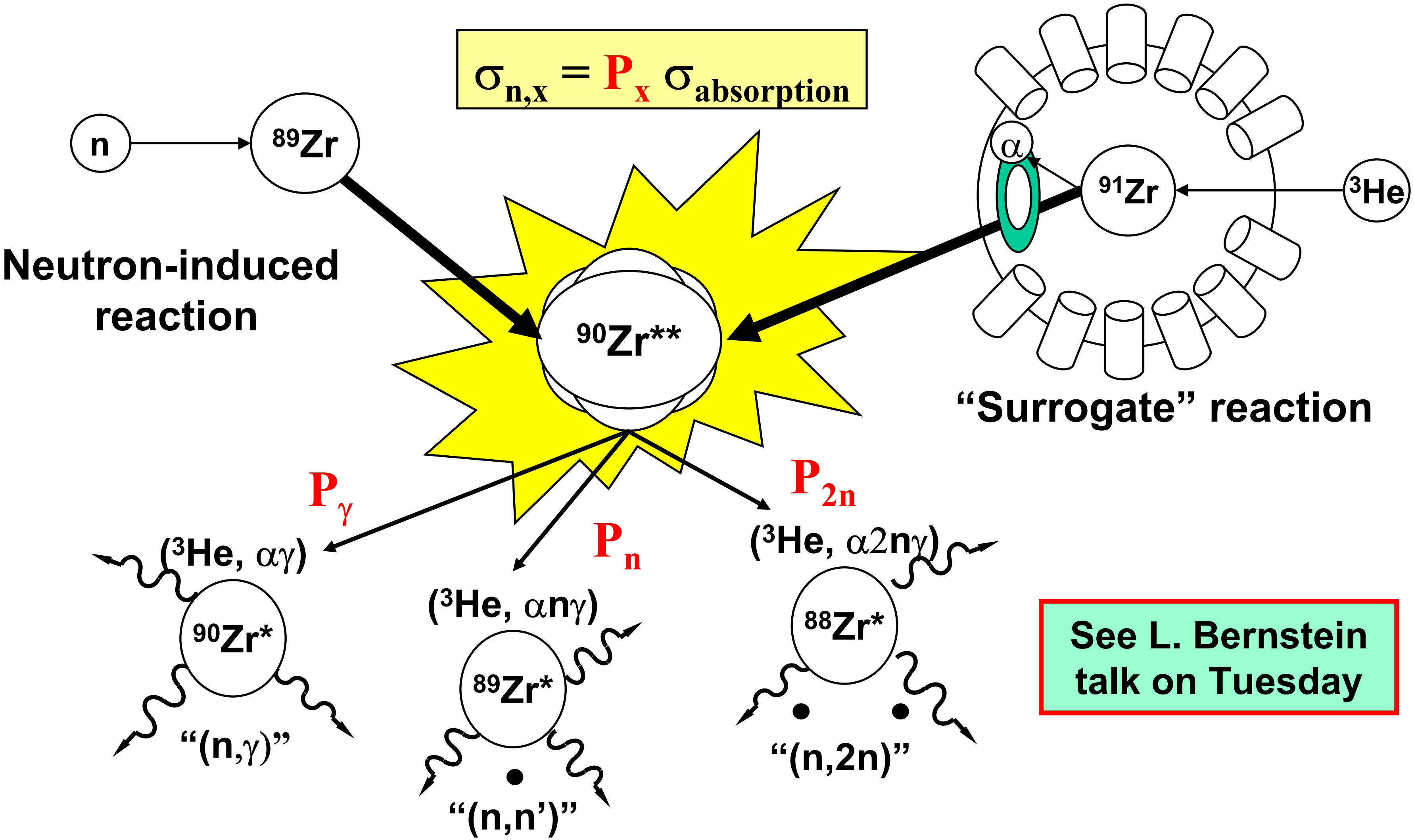
Number of target atoms small because of short half-life.

- **Largest production rates at radioactive beam facilities is 10^{12} pps.**
- **10^{12} pps implies 10^{17} atom limit for isotope with one day half-life.**

Nuclear cross-sections are small, typically 0.1-1 barn.

10^{17} atoms of one day half-life implies 1000 decays per nanosecond.

Example of Surrogate Reaction Technique



- Technique measures decay probabilities, P_x (shape of cross section).
- Normalization required from optical model or direct measurement

The Surrogate Reaction Technique – Advantages and Issues

Advantages

- Avoids neutron beams
- Simultaneous measurement of all reactions on single nuclei
- Simultaneous measurement at all energies.
- Depending on what reactions can be used
  - Simultaneous measurement of reactions on several nuclei
  - Avoids radioactive targets

Issues

- Normalization: Direct measurement or Optical Model?
- What reactions can be used?
- What range of energies?
- Practicality of technique in reverse kinematics?

Reach of Stable Beam Surrogate Experiments

Lutetium network (A=170-179) and adjacent nuclei

Hf	171	172	173	174	175	176	177	178	179	180
Lu	170	171	172	173	174	175	176	177	178	179
Yb	169	170	171	172	173	174	175	176	177	178

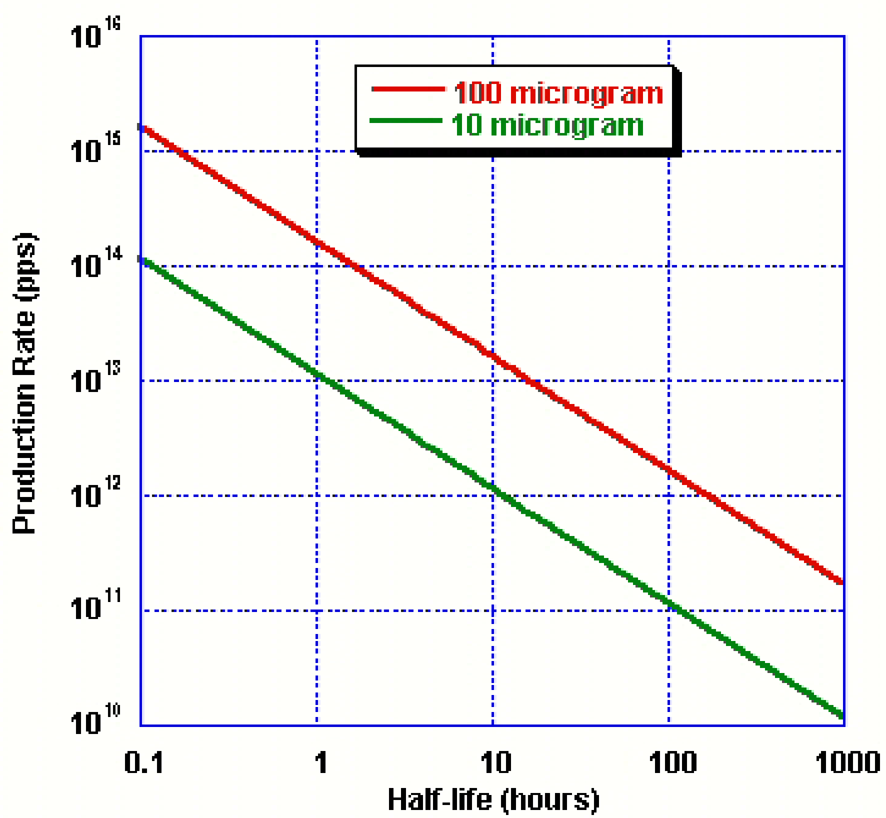
naturally occurring 1 day – 10 y half-life < 1 day half-life

- d,p reactions require same target as direct neutron experiments
- neutron surrogate reactions such (^{3}He,α), (α,α') expand reach
- surrogate reactions involving proton transfer maximize surrogate extent

RIB Facilities and Direct Measurements

RIB facilities in general and RIA specifically will enable direct neutron cross-section measurements on many short lived nuclei

Production Rate vs. Half-life



- **Maximum production rate from present and planned radioactive ion beam facilites: $10^{12\text{-}13}$.**
- **10 μg of material should be enough to do most measurements.**
- **Some can be done with less material, though few could be done with less than 1 μg.**
- **One measurement – one energy point**

Several direct measurements plus surrogate measurement would be most efficient way to obtain data for all reactions and all energies

Prompt Fission Fragments

Monitoring fission is also important to stockpile stewardship

Zr	95 64.0 d	96 stable	97 16.8 h	98 30.7 s	99 2.2 s
Y	94 18.7 m	95 10.3 m	96 5.3 s	97 3.76 s	98 0.59 s
Sr	93 7.41 m	94 1.25 m	95 25.1 s	96 1.07 s	97 0.43 s
Rb	92 4.48 s	93 5.85 s	94 2.71 s	95 0.38 s	96 0.20 s
Kr	91 8.6 s	92 1.84 s	93 1.29 s	94 0.21 s	95 0.78 s

Peak of light mass fragment near A=95.

Peak of A=95 near ^{95}Sr.

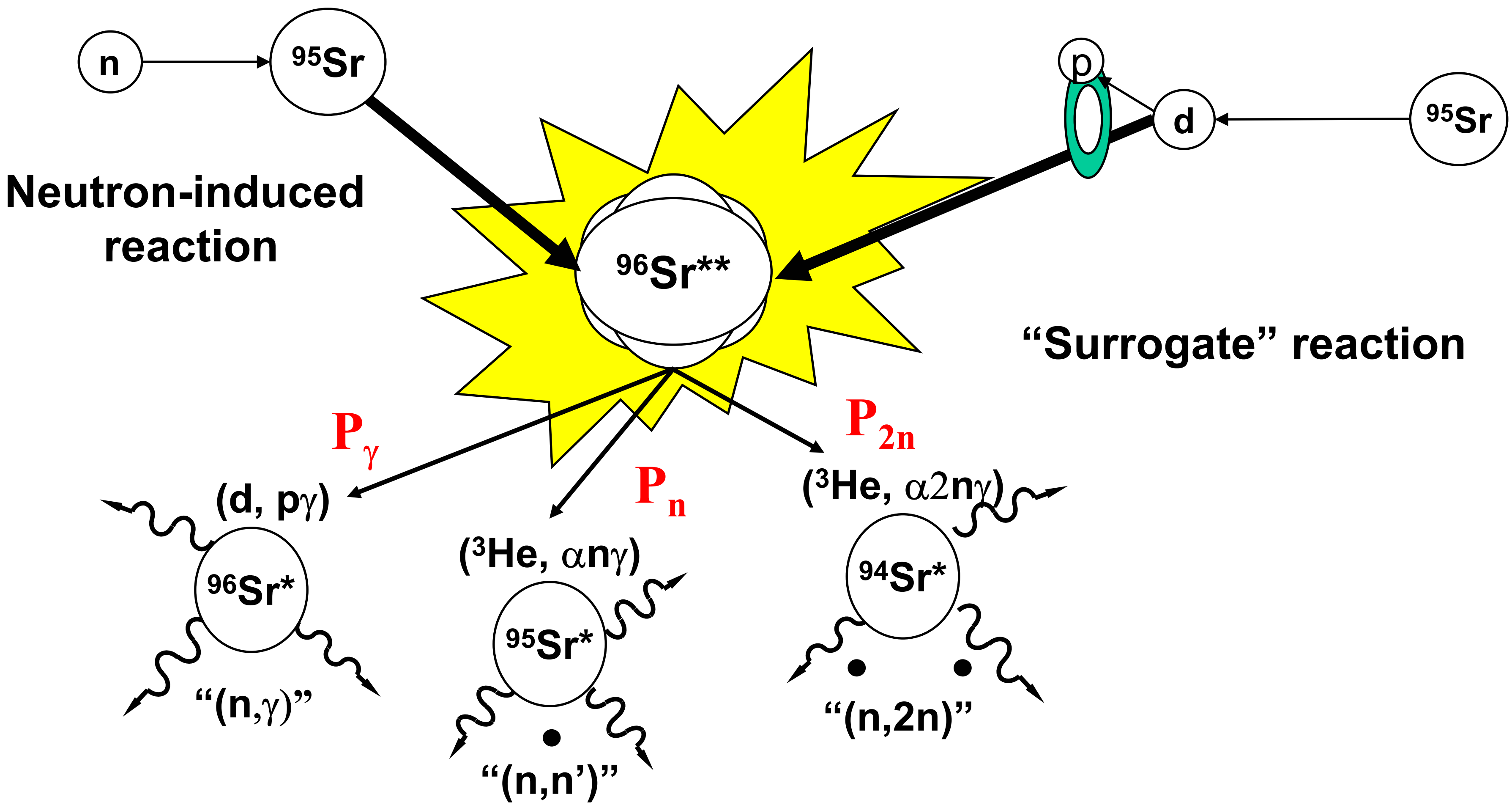
Most prompt fission fragments half-life times short compared to radiochemical recovery time.

How do subsequent neutron reactions change fission fragment distribution?

Half-life of nuclei too short for target formation – indirect method needed

Surrogate Reactions and Radioactive Ion Beam Facilities

Surrogate reaction technique in inverse kinematics would allow data to be obtained that could be obtained in no other way



Summary

- Stockpile Stewardship requires better knowledge of neutron cross-section information for many unstable nuclei.
- The Surrogate method offers an alternative to direct neutron cross-section experiments.
- The Surrogate method could allow information of neutron cross-section on unstable nuclei to be obtained by stable target charge particle beam experiment.
- The Surrogate method could also allow data to be obtained at RIB facilities that could not be obtained in any other way.